AN EVALUATION OF GREEN PROPELLANTS FOR AN ICBM POST-BOOST PROPULSION SYSTEM

Brian J. German*, E. Caleb Branscome*, Andrew P. Frits*, Nicholas C. Yiakas*, and Dr. Dimitri N. Mavris†
Aerospace Systems Design Laboratory
School of Aerospace Engineering
Georgia Institute of Technology
Atlanta, GA 30332-0150

ABSTRACT

Propellant toxicity is a major concern in storing, maintaining, and transporting strategic missiles. Many low toxicity "green" propellants have been developed which hold the potential of increasing the safety and lowering the operation and support costs of liquid-fuelled strategic missile propulsion systems. This study evaluates several green propellants for use in a notional next-generation post-boost propulsion system (PBPS). The mission and physical dimensions for this PBPS were defined by the requirements of the current Minuteman III propulsion system rocket engine (PSRE). Possible propellants were initially screened in terms of toxicity, performance, and technical feasibility for the PBPS application with a multi-attribute ranking method based on an overall evaluation criterion (OEC). Promising propellants were identified, and candidate PBPS concepts were developed and sized for each of these propellants. These concepts were evaluated in terms of weight, cost, and technical risk to determine which concepts, and hence propellants, show the most promise for the application. Probabilistic techniques were employed to explore the effects of uncertainty in the propellant performance and structural weight estimates. The results indicate that high-test peroxide (HTP) combined with either an ethanol-based nontoxic hypergolic miscible fuel (NHMF) or competitive impulse non-carcinogenic hypergol (CINCH) is a very viable propellant solution.

NOMENCLATURE

ACS	Attitude Control System
CDF	Cumulative Distribution Function
CINCH	Competitive Impulse Non-Carcinogenic Hypergol
DACS	Divert Attitude Control System
HTP	High Test Peroxide (High Concentration H_2O_2)
I_{sp}	Specific Impulse
HTPB	Hydroxy-Terminated Polybutadiene
MM	Minuteman
MM III	Minuteman III
MMH	Monomethyl Hydrazine
NIOSH	National Institute for Occupational Safety and Health
NHMF	Ethanol Nontoxic Hypergolic Miscible Fuel
NTO	Nitrogen Tetroxide
OEC	Overall Evaluation Criterion
PBPS	Post Boost Propulsion System
PBV	Post Boost Vehicle
PE	Polyethylene
PSRE	Propulsion System Rocket Engine
REL	Recommended Exposure Limits

* Graduate Research Assistant

† Director, Aerospace Systems Design Laboratory, Boeing Prof.

 Presented at 2000 Missile Sciences Conference, Monterey, CA.

INTRODUCTION

As evidenced by the Minuteman III and Peacekeeper systems, storable liquid rocket propellants have been historically preferred for land-based ICBM post-boost propulsion. Typically consisting of a hydrazine-based fuel and a nitrogen-based oxidizer, they have been selected for many ICBM upper stage and spacecraft applications because they offer very high performance for storable (non-cryogenic and non-degrading) propellants. The specific impulse for many of these formulations approaches 300 seconds. As hypergolic liquids (propellants that ignite automatically upon mixing) these formulations also allow for the precise thrust metering/impulse cycling necessary for the stringent angular positioning and range maneuvering requirements of the post-boost application.

These propellants have one major detriment, however: toxicity. Any significant exposure to either the liquids or vapors can be extremely harmful or fatal. A leak or spill could be devastating both in loss of life and in environmental damage. The threat of a spill incident mandates the need for costly safety systems and procedures and causes concern in transporting the propellants. Additionally, planned future reductions in exposure limits from the Occupational Safety and Health Administration (OSHA) and the National Institute for Occupational Safety and Health (NIOSH) will further constrain the handling of the propellants.

Based on these concerns, many new lower toxicity propellants have been undergoing development. These propellants include fuels such as dimethyl-2-azidoethylamine, known by the 3M trade name Competitive Impulse, Non-Carcinogenic Hypergol (CINCH)[1], and a doped ethanol Nontoxic Hypergolic Miscible Fuel (NHMF)[2,3] that may offer comparable performance to monomethyl hydrazine (MMH). Renewed interest in high concentration hydrogen peroxide, also called high-test peroxide (HTP), as a less hazardous oxidizer has also spurred significant research[4]. These, in addition to inherently less dangerous solid, hybrid, and gel formulations, are often classified as "green" propellants because of the lower environmental and personnel dangers that they pose compared to other high-performance propellants.

Although less toxic, these propellants do not have a proven record for ICBM application. Research and testing must prove them to be capable of hypergolic or near instantaneous ignition, to provide high levels of specific impulse, and to be storable without significant degradation for a service life of as much as 30 years. Hypergolicity is a challenge because many of the proposed formulations require soluble catalysts to provide the capability. Storage life is a concern for HTP because it degrades significantly over time at normal storage temperatures.

This study evaluates the potential of the various green propellants for use in a notional next-generation Post-Boost Propulsion System (PBPS). The authors assert that the most effective method of implementing this evaluation is through discerning the *system level* effects of the propellant selection. This evaluation is accomplished by the following process:

- Identify propellant formulations that have the most potential for the application
- Formulate and size a PBPS concept for each propellant, incorporating proposed propulsion technologies that may be required to realize system performance
- Evaluate the concepts in terms of key metrics such as weight, cost, and technical risk

To identify green propellants with the most potential for the application, an Overall Evaluation Criterion (OEC) method was used. This method allowed the ranking of propellant candidates based on qualitative and quantitative attributes such as performance, system complexity, and toxicity. After comparing propellant combinations through the OEC method, the most plausible candidates from each propellant "family" (e.g. liquid, solid, etc.) were selected for further analysis. A PBPS concept was sized for each candidate propellant based on extrapolations from current systems. These concepts were then compared based on considerations such as their total weight, cost, and possible technology development issues. These results were used to draw conclusions on the applicability of the various green propellants for a future PBPS system. This process is summarized in Figure 1.

The current Minuteman III Propulsion System Rocket Engine (PSRE) uses monomethyl-hydrazine and nitrogen tetroxide, two highly toxic hypergolic propellants that provide good specific impulse as well as the rapid restart capabilities required for the precise positioning of multiple reentry vehicles. For the purposes of this study, the MM III PSRE has been taken as the archetype for the mission definition and physical dimensions of the candidate concepts.

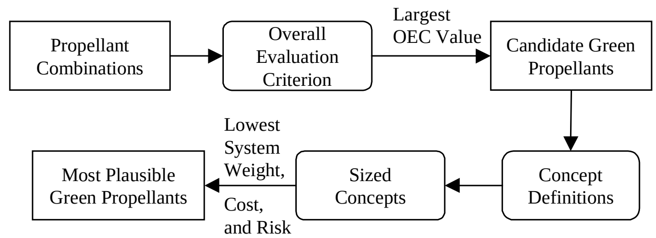


Figure 1: Overview of Propellant Evaluation Method

PROPELLANT IDENTIFICATION

As a first step in identifying candidate green propellants, extensive data available in the literature were collected for a wide variety of propellant formulations. The data consisted of metrics that are valuable for evaluating propellant applicability in the areas of environmental and/or personnel hazard (i.e. "greenness"), performance, and PBPS design integration. The following quantitative metrics were compiled for each propellant formulation:

- Mixture ratio
- Densities of oxidizer and fuel
- Viscosities of oxidizer and fuel
- Vapor pressures of oxidizer and fuel
- Frozen equilibrium specific impulse for an expansion from 300 psia to 14.7 psia
- National Institute for Occupational Safety and Health (NIOSH) recommended exposure limits (REL) for oxidizer and fuel

The NIOSH recommended exposure limits were used to quantify propellant toxicity because these are the most stringent government guidelines[5].

In addition to these quantitative metrics, qualitative rankings were established for certain characteristics that are either not easily represented as continuous numeric values or not widely available other than as generalizations. These rankings were specified as integers ranging from one to five with three corresponding to the metric ranking of the current MM III PSRE, one corresponding to significantly worse than the existing system, and five indicating significantly better than the baseline. These metrics include the following:

- Storability of oxidizer and fuel
- Ease of inerting oxidizer and fuel

- Ignition delay
- Complexity of implementing the propellant in a propulsion system

Data was obtained for 68 distinct propellant formulations (i.e. combinations of oxidizer and fuel at a certain mixture ratio) that have been used in production rocket engines or have been studied extensively in laboratory experiments. These formulations include liquid (including mono- and bi-propellants), solid, hybrid, and gel propellants. In addition to green propellants, traditional propellant formulations were included for comparative purposes. Cryogenic propellants were eliminated from consideration because of their incompatibility with the Minuteman infrastructure and their very low storage lives, and gaseous propellants were omitted because their very low density make packaging impractical. The propellant data was culled from several sources including technical reports and papers, the proceedings of the Second International Hydrogen Peroxide Propulsion Conference, the NIOSH internet web site, and the Weight Engineers Handbook. These sources are listed as references 6-13.

In order to identify the propellants that represent the most suitable blend of performance and "greenness", an overall evaluation criterion method was used. The OEC is a single numerical metric that can be used to compare alternatives. The OEC is formulated such that higher values represent more highly preferred solutions. The core of the OEC method is its defining equation. The equation consists of a sum of several terms, each of which represents a particular characteristic upon which the alternative is evaluated[14]. Each term is formed as a quotient comprised of the value of the respective characteristic for a particular alternative and the value for a chosen baseline alternative. Because higher values of the OEC are intended to represent more favorable options, the numerator and denominator of this quotient are interchanged as necessary to obtain the desired direction of optimality. For instance, if increasing a certain metric is desirable, the value for the alternative is placed in the numerator with the baseline value in the denominator. This formulation will yield a value of the quotient greater than 1.0 for an alternative with a higher value of the metric than the baseline. The ratio is inverted for metrics that are more desirable when minimized. The general form of the OEC equation is shown in Figure 2.

Weights indicate importance of metric in decision

$$OEC = \alpha\left(\frac{Metric}{Baseline\ Metric}\right) + \beta\left(\frac{Baseline\ Metric}{Metric}\right) + \gamma\left(\frac{Metric}{Baseline\ Metric}\right)$$

Maximize Metric   Minimize Metric   Maximize Metric

Figure 2: General Form of the OEC Equation

As shown in the figure, the terms of the OEC equation are preceded by scaling factors. These factors are used to weight the importance of each term relative to the OEC metric. The weights are chosen as fractions whose sum is 1.0. By choosing such a format, the value of the OEC for the baseline alternative is 1.0. Alternatives with an OEC value greater than that of the baseline are more desirable, while alternatives with values less than the baseline are less favorable.

For the purposes of propellant selection, an OEC equation was developed that is a function of the previously identified propellant metrics. The OEC is shown in Equation 1 below.

Equation 1: Propellant Selection OEC

$$\mathrm{OEC} = \alpha\left(\frac{\text{Specific Weight}}{\text{Specific Weight}_{\mathrm{BL}}}\right) + \beta\left(\frac{\mathrm{Isp}}{\mathrm{Isp}_{\mathrm{BL}}}\right) + \gamma\left(\frac{\text{Greenness}}{\text{Greenness}_{\mathrm{BL}}}\right) + \delta\left(\frac{\text{Sys.Complexity}}{\text{Sys.Complexity}_{\mathrm{BL}}}\right) + \varepsilon\left(\frac{\text{Ignition Delay}_{\mathrm{BL}}}{\text{Ignition Delay}}\right)$$

The specific weight and greenness terms shown in the equation are defined as functions of multiple metrics. The specific weight is the inverse of the weighted average of the oxidizer and fuel densities. As such, it is a function of mixture ratio that indicates the volumetric efficiency of the propellant combination. Equation 2 shows the expression for the greenness metric. Formulated as a general indicator of the propellant environmental and personnel hazard, it is intended to capture not only the direct toxicity of the propellant but also the ease of containing and inerting any propellant spills. For this reason, it was specified as a function of the REL to indicate toxicity directly and metrics such as vapor pressure (VP) and ease of inerting to indicate the hazard associated with a propellant leak. The logarithms of the REL and vapor pressure metrics that appear within the equation are used to compress the orders of magnitude variations that can occur in the parameters for different propellants into a linear form suitable for application in an OEC.

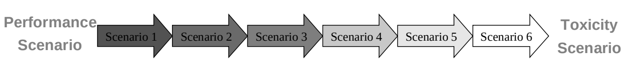
Equation 2: Toxicity OEC Term

$$\gamma\left(\frac{\text{Greenness}}{\text{Greenness}_{BL}}\right)=\frac{\gamma}{6}\left[\left(\frac{\log(100*\text{Ox. REL})}{\log(100*\text{Ox. REL}_{BL})}\right)+\left(\frac{\log(100*\text{Fuel REL})}{\log(100*\text{Fuel REL}_{BL})}\right)+\left(\frac{\log(\text{Ox. VP}_{BL})}{\log(\text{Ox. VP})}\right)+\left(\frac{\log(\text{Fuel VP}_{BL})}{\log(\text{Fuel VP})}\right)+\left(\frac{\text{Inert Ox.}}{\text{Inert Ox.}_{BL}}\right)+\left(\frac{\text{Inert Fuel}}{\text{Inert Fuel}_{BL}}\right)\right]$$

This OEC method for propellant selection is not unique and does not necessarily assure the best selection. It is only one of several decision methods for ranking alternatives based on subjective and objective data. It also suffers from some shortcomings including the presumption that all attributes are independent. The OEC method was chosen, however, because it was tractable and provided good visibility and traceablity for the propellant pre-screening process.

After developing the propellant evaluation OEC equation, a series of weighting scenarios was developed against which the propellants should be judged. Each scenario is comprised of a set of weighting scalars, whose sum is 1.0, that indicate the relative importance of each metric to the OEC. Multiple scenarios were used to prevent a biasing of the results caused by a single particular choice of weightings. This method ensures that no propellants are eliminated from consideration because of poor performance on only one scenario. Propellants were judged on their suitability across the entire spectrum of scenarios studied. Table I shows the scenarios developed for propellant screening. As shown in the table, the six scenarios range successively in emphasis from performance to toxicity.

Table I: Propellant Evaluation Scenarios



Scenario	*Specific Weight,* α	*Isp,* β	*Toxicity,* γ	*System Complexity,* δ	*Ignition Delay,* ε
Performance (1)	0.3	0.5	0	0.1	0.1
2	0.3	0.4	0.1	0.1	0.1
3	0.3	0.3	0.2	0.1	0.1
4	0.25	0.25	0.3	0.1	0.1
5	0.25	0.25	0.4	0.1	0
Toxicity (6)	0.2	0.2	0.5	0.1	0

Using the weightings within each scenario, the OEC was calculated for each propellant within the database using the current MM III PSRE propellants, NTO and MMH, as the baseline. From the results, the propellant within each family with the highest average OEC value across the scenarios was noted. An example of this "average" OEC performance for some of the propellants examined is shown in Figure 3. In this excerpt from the OEC results, it is clear the HTP/ethanol NHMF is, *on average*, superior to the other propellants listed for the spectrum of weighting scenarios considered. The HTP/CINCH formulation closely follows. It is interesting to note that the HTP/NHMF is superior to the NTO/MMH that is used in the current PSRE in every case except for the purely performance weighted scenario in which it trails only slightly. The CINCH formulation outperforms the NTO/MMH even for the performance scenario.

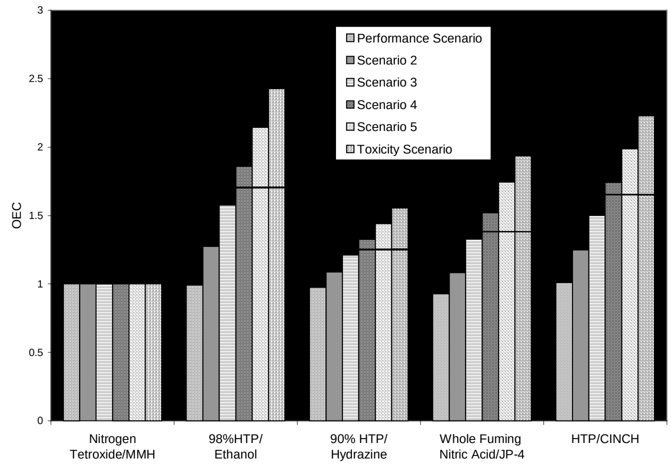


Figure 3: Example of Average OEC Across the Spectrum of Scenarios

The propellants within each family of similar concepts (e.g., liquid, solid, etc.) with the highest average OEC performance were selected as candidates for which a sized PBPS concept would be developed. These propellants are the following:

- Ethanol Nontoxic Hypergolic Miscible Fuel (NHMF) / High Test Peroxide (HTP) liquid
- Competitive Impulse Non-Carcinogenic Hypergol (CINCH) / HTP liquid
- Monomethyl hydrazine (MMH) / nitrogen tetroxide (NTO) loaded gel
- Polyethylene (PE) / HTP hybrid
- Aluminum / hydroxy-terminated polybutadiene (HTPB) / ammonium perchlorate solid

Figure 4 shows the weighted values of each OEC term for the selected liquid, hybrid, and gel propellants evaluated for the performance and toxicity scenarios. Because desirability relative to the baseline is comprised of OEC values greater than 1.0, it is clear that all of the selected propellants exhibit significantly lower toxicity and, at worst, only marginally decreased performance relative to the MMH/NTO liquid used in the existing MM III PSRE. These results indicate that the selected green propellants should prove good candidates for the PBPS application.

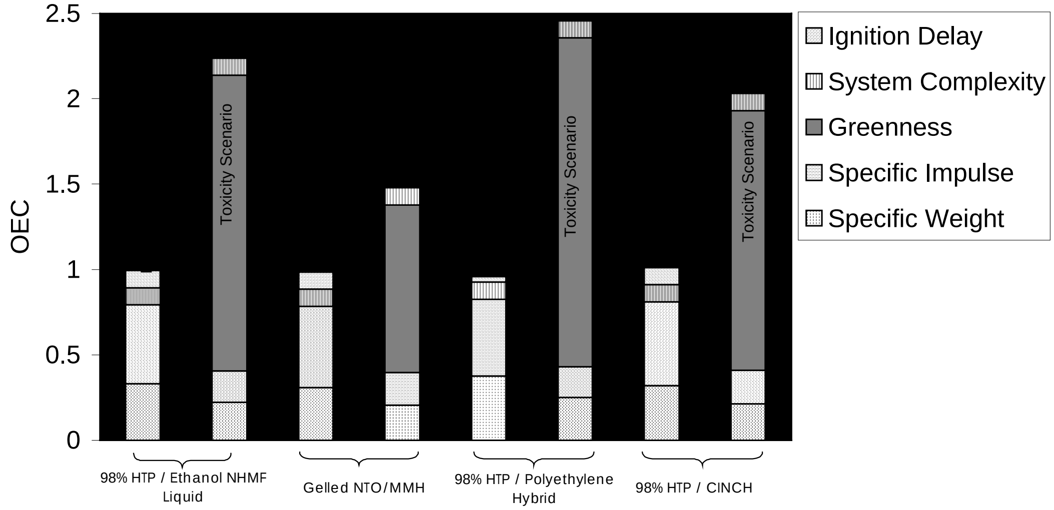


Figure 4: OEC Component Breakdown for Selected Propellants

		Post Boost Propulsion System Concepts					
		Current PSRE	1	2	3	4	5
Primary Propulsion System	Propellant	MMH / NTO liquid	HTP / alcohol liquid	HTP / CINCH liquid	HTP / polyethylene	NTO / MMH gel	HTPB / ammonium perchlorate solid
	Thrust metering system	valving	valving	valving	valving	valving	pintle/hot gas bypass system
	Thrust vectoring	gimballed engine	gimballed engine	gimballed engine	gimballed engine	gimballed engine	gimballed engine
Attitude Control System	System type	ducted primary propellant thrusters	ducted primary propellant thrusters	ducted primary propellant thrusters	ducted primary propellant thrusters	ducted primary propellant thrusters	ducted hot gas thrusters/DACS
	Thrust metering system	valving	valving	valving	valving	valving	hot gas bypass system
Propellant Expulsion and Distribution Systems	Feed system	pressurized cold gas	pressurized cold gas	pressurized cold gas	pressurized cold gas	pressurized cold gas	no feed system
	Pressure tank shape	cylindrical	spherical	spherical	spherical	spherical	no tank
Propellant Storage Assemblies	Fuel tank shape	cylindrical	spherical	spherical	cylindrical	spherical	cylindrical thrust chamber
	Oxidizer tank shape	cylindrical	spherical	spherical	spherical	spherical	integral to fuel tank/thrust chamber

Figure 5: Matrix of Candidate PBPS Concepts

CANDIDATE CONCEPT DEFINITION

In order to develop a PBPS concept for each propellant, several alternative subsystem design and technology concepts were explored. The subsystem categories include the primary propulsion system, the attitude control system, the propellant expulsion and distribution systems, and the propellant storage assemblies. Structural support alternatives were not initially explored during the development of PBPS concepts. This decision to isolate structural technologies was made in order to allow comparison of the concepts only through the implications of the propellant selection on the subsystem and components.

For the purposes of developing conceptual configurations, modified versions of the aluminum/magnesium monocoque structure from the existing MM III PSRE were assumed.

The principal design decisions in the development of a PBPS configuration are those defining the primary propulsion system. The primary propulsion system design decisions were classified as selection of the propellant formulation, the impulse cycling method, and the thrust vectoring technique. Because concepts were developed for each propellant formulation, the decisions on impulse cycling and vectoring must correspond to the particular propellant.

Based on these subsystem alternatives, a notional PBPS subsystem configuration was developed for each of the five selected propellants. The five configurations are outlined in Figure 5. These configurations were formed by considering the subsystem options that were expected to yield the minimum weight and minimum technological risk solutions. For instance, all of the configurations employing liquid propellants contain spherical propellant storage tanks. Trade studies indicated that these tanks provided the minimum weight solutions and could be packaged within the dimensional envelope of the current MM III PSRE. Also, the liquid systems were all designed with cold gas expulsion systems. Cold gas systems were believed to provide lower weight (relative to a pump) and more accurate expulsion control (relative to a hot gas system). For thrust vectoring, all designs incorporate mechanically gimbaled engines. These systems were viewed to be potentially lighter and lower risk than fluidic control, jet tabs, or jet vanes.

The systems incorporating solid propellant components have some significant differences from the liquid propellant concepts. For instance, both the hybrid HTP/PE and the solid ammonium perchlorate/HTPB system use cylindrical fuel storage assemblies that serve as the combustion chambers. The cylindrical design allows for integration of a solid grain conducive for even burning. In the pure solid system, the oxidizer consists of grains commingled with the fuel, while in the hybrid system, the oxidizer is stored as a liquid in separate spherical tanks. These concepts also have significantly different attitude control systems (ACS) configurations than their liquid counterparts. The hybrid system uses the oxidizer as a monopropellant for the attitude control engines. The pure solid system employs ducted hot gas from the solid propellant gas generators and a divert attitude control system (DACS) to provide a multi-tiered approach to attain precise vernier positioning.

HTP/NHMF, HTP/CINCH LIQUID CONCEPTS

The schematic for the HTP/NHMF concept is shown in Figure 6. The HTP/CINCH concept is identical except for the change in fuel (and the corresponding tank sizing). One of the major design challenges that must be overcome in developing a feasible HTP system is the mitigation of the oxidizer's tendency to degrade. High purity HTP is required to maintain acceptable levels of performance; however, HTP slowly decomposes to water and oxygen. This decomposition is a strong function of temperature. At a typical silo temperature of 70°F, the HTP decomposition rate is between 1% and 2% per year[15]. With a 1%/year rate, HTP at an initial concentration of 98% degrades to 72.5% concentration within the 30 year storage life expected for the next generation PBPS. If it is maintained at a temperature near 25°F, however, the yearly decomposition rate is reduced to approximately 0.01%. This rate of decomposition means that an initial concentration of 98% HTP would decompose to 94.5% during the 30 year storage life. This level of degradation is manageable from a propellant sizing standpoint.

One possible solution to hold the hydrogen peroxide temperature near 25°F during nominal silo storage is to attach solid-state cooling devices, called thermo-electric coolers (TECs) to the oxidizer tanks. These devices are commercially available, inexpensive, lightweight, and have demonstrated 30 years of continuous operation in space-based applications[15]. Due to their low weight and cost, the TECs could be made multiply redundant.

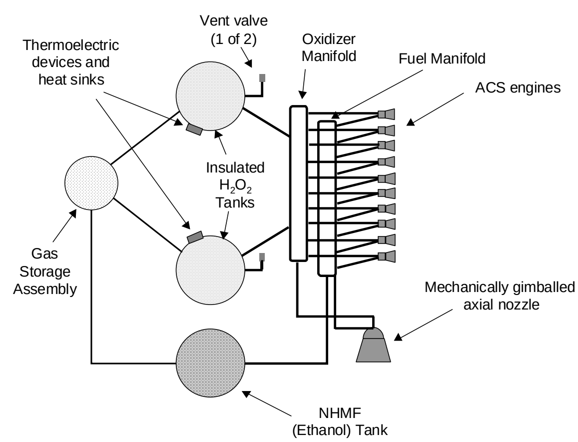


Figure 6: HTP/NHMF Candidate Schematic

NTO/MMH LOADED GEL CONCEPT

The NTO/MMH gelled propellant concept consists of a single spherical oxidizer storage assembly, a spherical fuel storage assembly, and a spherical gas storage assembly in addition to the axial and attitude engines.

One of the key drivers of the gelled propellant design is the high system pressure that is required. Because the gels are thixotropic (they become liquid under pressure), high pressures are needed before the gels will flow through the propellant ducting. In order to handle the system pressures, both the gas and propellant storage assemblies and the propellant distribution system must be strengthened, adding significant weight to the structure.

Another unique challenge of the gelled propellant concept is design of the engine propellant valves. Although loading the gelled fuel with aluminum particulates increases the propellant performance, the particulates have a tendency to clog valves and injection orifices. Because of the technological risk associated with a large loading fraction, the concept for this study employs only the minimal loading level required to negate the performance degradation due to the presence of the gellant material. This low level of loading should preclude the need for complex valve assemblies, but some changes over a liquid system may prove necessary. If future studies indicate that valve clogging will be an issue, a valve design employing a translating centerbody with a wiping capability could be incorporated.

HTP/POLYETHYLENE HYBRID

The primary assemblies comprising the configuration of the HTP/polyethylene hybrid concept are three HTP oxidizer storage assemblies, a gas storage assembly, and a fuel storage/combustion chamber. The necessity for three oxidizer storage assemblies is driven by the high value of the optimum mixture ratio. Correspondingly, the fuel storage/combustion chamber is comparatively small.

The primary advantage of a hybrid propulsion concept is that it incorporates many of the favorable characteristics of both liquid and solid propellant systems. As with liquid systems, hybrid engines allow impulse cycling. This cycling is achieved by incorporating a throttleable valve that controls the oxidizer injection into the combustion chamber. The hybrid system gains two critical advantages over liquid rocket systems. These are the increased density and decreased environmental hazard of the fuel. Because of the increased density, more fuel mass can be packaged in a smaller volume. This characteristic is especially advantageous for a volume-constrained upper stage application such as a PBPS. The solid fuel has a very low environmental and personnel hazard both because it cannot leak and flow and because it has negligible toxicity.

In order to facilitate thrust chamber packaging, a circumferential swirl injection combustion chamber design was adopted. This design concept, similar to the Surrey Vortex Flow “Pancake” Engine[16], allows a low aspect ratio construction because oxidizer is injected at ports located around the circumference of the combustion chamber rather than in one. The injectors are oriented such that the liquid stream has a significant circumferential component. This orientation causes the oxidizer to “swirl” around the combustion chamber toward the center in a similar fashion as water drains from a sink. As combustion occurs, the hot gas is expelled through the centrally located nozzle throat. The general configuration of this concept is shown in Figure 7.

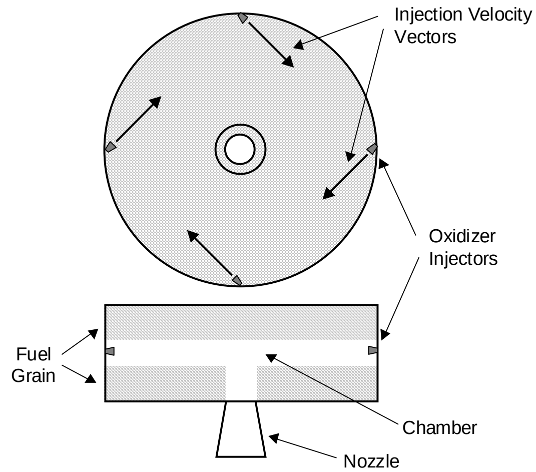


Figure 7: Circumferential Swirl Injection Thrust Chamber

This “swirl” effect has additional advantages. The circumferential component of the oxidizer injection velocity serves to improve propellant mixing and to reduce the chamber size necessary to achieve a residence time greater than the ignition delay. The swirling also results in a layer of cool oxidizer on the periphery of the combustion chamber. This layer shields the chamber walls from high heat loads.

Another unique feature of the HTP/PE concept is the design of the attitude control engines. Hybrid systems are often characterized by poor ignition delay times, so the development of an effective ACS engine may involve significant technical risk. An ACS thruster concept that uses HTP as a monopropellant may prove more risk averse. The hydrogen peroxide fuel can be used as a monopropellant by catalyzing the HTP such that it exothermically decomposes into water vapor and oxygen gas[17]. The resulting hot gaseous products can be expelled through a nozzle to produce the required thrust. Though the reaction time of this catalytic HTP decomposition would not be low enough to ensure an adequate ignition delay and minimum impulse for the ACS engines, an integral accumulator reservoir within the ACS engine has been incorporated for storing catalyzed decomposition products. The presence of this tank within the thrusters allows the HTP to be catalyzed in a quasi-steady manner such that hot gas is always available for rapid engine firings. This thruster configuration is depicted in Figure 8.

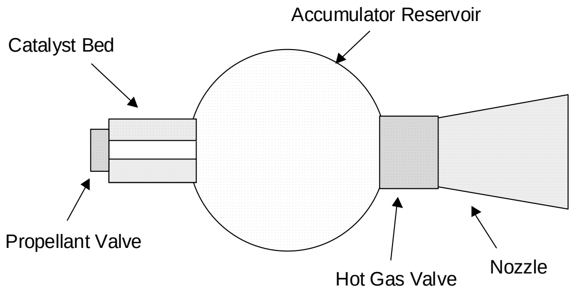


Figure 8: HTP Monopropellant ACS Engine

Although the HTP monopropellant thruster concept should overcome the issue of ignition delay for the ACS engines, ignition delay could remain a problem for the axial engine. Many current hybrid rocket engines have ignition delays of several seconds. Such delays are unacceptable for the PBPS application. This concern is amplified by the fact that hybrid motors have not been demonstrated for upper stage application. An additional concern for the hybrid concept is in packaging the combustion chamber. The low aspect ratio of the chamber allows it to fit within the outer PBPS geometric envelope, but sizing studies have indicated that a purely cylindrical chamber may intrude into the volume occupied by the guidance set gyro platform of the current MM III. This intrusion would necessitate a more complicated combustion chamber geometry. All of these concerns indicate that a hybrid concept would entail significant developmental risk.

SOLID PROPELLANT CONCEPT

Figure 9 depicts a schematic of the aluminum/ HTPB/ammonium perchlorate solid propellant concept. The concept consists of three primary solid propellant gas generators, three vernier positioning gas generators, and a final positioning divert attitude control system. This 3-tiered propulsion scheme is the key attribute of the solid propellant concept.

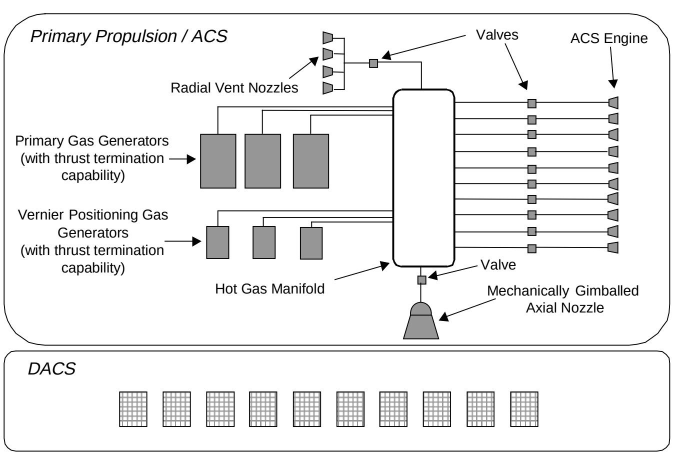


Figure 9: Solid Propellant PBPS Concept

To attain acceptable levels of pointing accuracy and precise downrange and crossrange velocity increments, a PBPS design must allow high fidelity thrust control for both the axial and the attitude control engines. This thrust control is characterized by a small minimum impulse capability, low ignition delay, and impulse cycling capability. A high level of thrust control is difficult to achieve in solid propellant systems because the engines fire at a designed burn rate until all of the propellant is expended. Although some control may be afforded by designing the propellant grain structure to vary thrust over a certain profile during the burn, the exact burn profile requirement for a given PBPS mission cannot be known *a priori* and certainly cannot be generalized to a single grain design. This difficulty arises from the flexibility that the PBPS must afford: it must be capable of correcting any positioning errors resulting from the boost phase of the mission, and it must allow independent targeting of three RVs over a wide range of flight paths. To allow this flexibility within a solid propellant system, a multi-tiered "tunneling" approach was devised to attain accurate positioning. The system envisioned for this study consists of three discrete levels of propulsive capability in which each subsequent tier provides more precise thrust control that can correct for the positioning errors imposed by the previous propulsive level.

The first propulsive tier is provided by three primary gas generators. These solid propellant thrust chambers are fired to produce major velocity increments for bulk downrange and crossrange maneuvering. One primary chamber is provided for each RV. The chambers are connected to the attitude control and axial nozzles via high-temperature hot gas ducting. During a burn, the effluent products from the chamber provide both axial and attitude control thrust. Should the thrust requirements at a given point during the burn be less than the capability of the chamber, the excess hot gas is expelled through a series of radially-oriented vent nozzles. These nozzles are placed symmetrically around the PBPS circumference and opened in unison such that the net radial thrust is negligible.

Three vernier positioning gas generators comprise the second tier of the propulsion system. These chambers, similar to those employed by the Trident SLBM[18], are fired to allow positioning during "coast" phases between major downrange or crossrange maneuvers. Although connected to the same hot gas manifold as the primary gas generators so that both axial and ACS impulse can be provided, the vernier positioning chambers are sized primarily for the ACS duty cycle.

The final level of propulsive control is afforded by the divert attitude control system. This system consists of multiple banks of small solid propellant impulse charges that are oriented in a pattern similar to that of the 10-engine primary ACS of the current MM PSRE. These charges are used to provide precise positioning of the post-boost vehicle (PBV) immediately prior to RV release. Because the impulse of these charges is small and can be accurately predicted, multiple charges can be fired immediately before each release to damp out angular positioning errors and to allow PBV back-away from the RV without applying any significant jolt to the RV being released.

Although this solid propellant concept offers significant advantages in propellant "greenness", it has several disadvantages. One issue is weight. The hot gas ducting and valves needed for this concept must be fabricated from materials capable of withstanding high temperatures and pressures. For this reason, the hot gas distribution system will be heavy. The use of multiple combustion chambers also amplifies structural weight significantly. In addition to high weight, the concept is also very aggressive from a technology standpoint. Although some elements of the concept have been demonstrated in the Trident SLBM system, the technological risk associated with the hot gas distribution system and the DACS is significant. Also, a solid propellant system has not been demonstrated for the stringent land-based ICBM accuracy requirements. Another disadvantage of the solid propellant system is that the propellant is a dangerous ordnance item.

CANDIDATE CONCEPT SIZING

Candidate concepts were sized by using a rocket equation approach. Each sized candidate concept was provided with enough propellant mass to maintain the same velocity budget as the current Minuteman III system (including boost stages and the PSRE). PBPS empty weight was estimated by scaling the current PSRE sub-system weights based on propellant mass and pressure. Figure 10 presents the methodology formulated used for sizing the candidate concepts. Assumptions for the concept sizing are listed in Table II. Additional details on the sizing process are presented in reference 15.

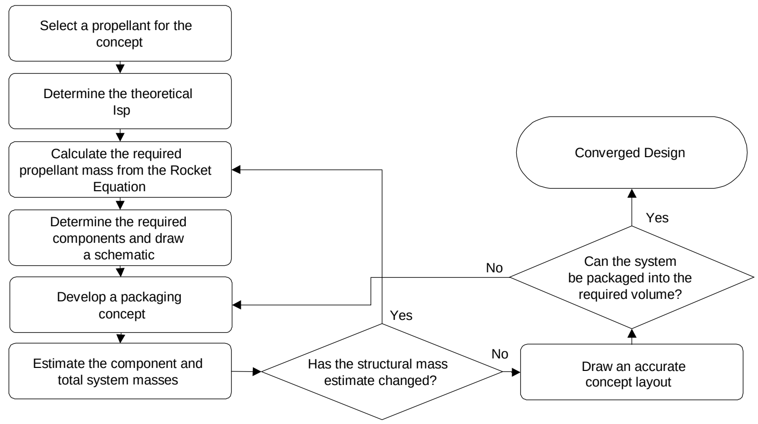


Figure 10: Concept Development Process Flowchart

Table II: Table of Sizing Assumptions and Characteristics

Sizing Characteristic	*Sizing Assumptions*
Chamber pressure for liquid concepts	Fixed for all concepts at 125 psia
Chamber pressure for solid, hybrid, and gelled concepts	Fixed for all concepts at 600 psia
Expansion ratio/exit pressure	Fixed to estimated baseline expansion ratio of 26 for all except hybrid, which was sized for fixed length nozzle with correspondingly higher expansion ratio
Structural weight	Fixed for all concepts
Propellant storage assemblies	Scaled according to required chamber pressures, fuel volumes, mixture ratios and densities
Gas storage assemblies	Scaled according to required chamber pressure
Fittings (pressure transducers, filters, squibs, etc.)	Weight fixed, but quantity adjusted according to concept

Examples of concept layouts are given in Figure 11. Converged weight breakdowns for the systems are given in Table III.

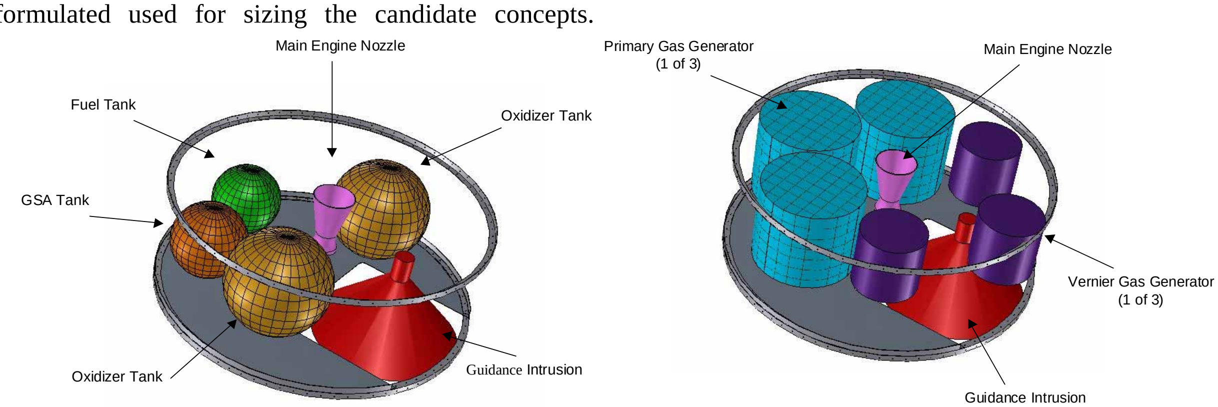


Figure 11: Layout of HTP/NHMF Concept (left) and Solid Propellant Concept (right)

Table III: Converged Mass Breakdowns for the Candidate Systems

	Current MMIII PSRE (Estimated) ‡	*HTP/ NHMF*	*HTP/ CINCH*	*HTP/PE*	*NTO/MMH Gel*	*Solid*
System Average Isp (sec)	280.2	269.8	273.9	274.1	284.7	264.7
Subsystem	***Mass (lbm)***	***Mass (lbm)***	***Mass (lbm)***	***Mass (lbm)***	***Mass (lbm)***	***Mass (lbm)***
Gas Storage Assembly	55.0	55.0	55.0	26.0	60.0	--
Internal Structure	27.0	27.0	27.0	27.0	27.0	27.0
Rocket Engine Assemblies / Thrust Chamber Assemblies	69.0	69.0	69.0	82.0	69.0	72.0
Pyrotechnic Command Cable	7.0	7.0	7.0	7.0	7.0	7.0
Thruster Actuation and Gimble Command Cable	14.0	14.0	14.0	14.0	14.0	14.0
Thermal Insulation Blanket Assembly	15.0	15.0	15.0	15.0	15.0	15.0
External Shell/Interstage Assembly	73.0	73.0	73.0	73.0	73.0	73.0
Propellant Distribution System	19.5	19.5	19.5	10.8	19.5	--
(Propellant Gas Combustion and Distribution System)	---	--	--	--	--	216.6
Oxidizer Propellant Storage Assembly	26.6	13.2	13.2	19.1	19.8	--
Fuel Propellant Storage Assembly / Solid Fuel Grain Casing	26.6	6.9	6.9	26.0	19.8	--
Fasteners / Miscellaneous	9.0	9.0	9.0	9.0	9.0	9.0
Oxidizer Coolant System	---	10	10	--	--	--
Total Structural Mass	***341.7***	***318.6***	***318.6***	***295.9***	***333.1***	***433.6***
Oxidizer Mass (Primary Gas Generator Propellant)	160.0	171.4	151.2	269.8	147.7	400.0
Fuel Mass (Secondary Gas Generator Propellant)	100.0	45.2	58.2	22.3	92.3	115.0
(DACS Propellant)	---	--	--	--	--	40.0
Total Propellant Mass	***260.0***	***216.6***	***209.4***	***292.1***	***240.0***	***555.0***
Total Mass	***601.7***	***535.2***	***528.0***	***588.0***	***573.0***	***988.6***

( ) indicates a subsystem that is only present in the solid propellant concept ‡ references *15,19, and 20*

UNCERTAINTY ANALYSIS

A refined version of the HTP/NHMF concept with additional weight savings achieved through modern structural technologies was chosen as an example to evaluate the effects of uncertainty in the sizing process on total PBPS weight. A probabilistic study was conducted to capture uncertainty in both the structural weight and the propellant specific impulse, as these parameters are the primary drivers on system sizing to meet the fixed performance requirements. The specific goals of the design study were as follows:

- Define reasonable bounds for uncertainty in the specific impulse and structural weight
- Bound the uncertainty in the total PBPS weight that might result from variation in the specific impulse and structural weight from their presumed values
- Ensure that the specific impulse and structural weight uncertainty does not result in an inability to create a sized design to meet the mission requirements

The first step in the study involved establishing bounds for the maximum expected uncertainty for the specific impulse and structural weight estimates. Because of a high confidence in the predicted propellant performance, a small uncertainty bound was placed on the nominal I_{sp} predictions. This uncertainty bound was set at ±2.5% of the calculated propellant $I_{sp.}$

The structural weight estimates, however, are more uncertain. This uncertainty is partially a function of the lower fidelity and predictive capability of the structural weight estimation method used in preliminary sizing. Another factor in the uncertianty is in the estimates of the fixed weights (e.g. valves, ducting, etc.). Because this uncertainty is signficantly greater, bounds of ±20% of the nominal structural weight estimate was chosen. Since the actual structural weight and I_{sp} values are *most likely* close to the nominal value, and because the likelihoods of errors being either high or low are likely equal, the parameters were defined as normally distributed random variables for the purposes of this probailisitic design study. In order to generate the mean and standard deviation necessary to define these variables, the nomial predictions were set as the means, and the standard deviations were chosen such that the predicted bounds in the uncertainties were set to enclose ± 3 standard deviations. An illustration of the random variable definition for I_{sp} is shown in Figure 12.

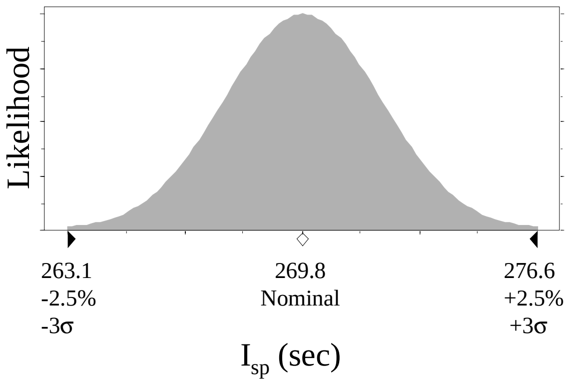


Figure 12: Specific Impulse Random Variable Definition

After the specific impulse and structural mass were defined as probability distributions, a Monte Carlo analysis was coupled with the PBPS sizing algorithm. In this analysis, the Monte Carlo simulation selected 10,000 discrete values of structural weight and specific impulse according to their respective probability distributions. The simulation then generated a sized PBPS concept for each of the 10,000 cases. The resulting PBPS total mass outputs from the sizing algorithm were collected to produce a cumulative distribution function (CDF). This CDF indicates the likelihood that the total mass is less than a specified value. The CDF for PBPS total mass is shown in Figure 13.

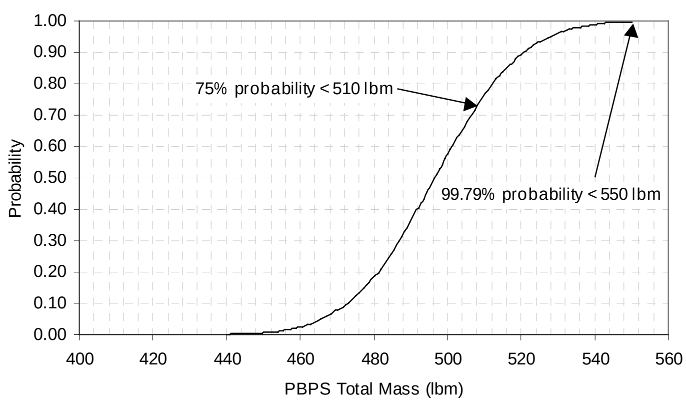


Figure 13: PBPS Total Mass Cumulative Distribution Function

The probabilistic analysis shows that likelihood of the PBPS weight being less than 550 lbm for the presumed uncertainty in structural mass and specific impulse is nearly 100%. This result indicates that the HTP/NHMF PBPS concept is certain to weigh less than the current MM III post boost system given the assumptions for structural weight and I_{sp} made in the study. The results also indicate that a HTP/NHMF PBPS can successfully be sized in the entire presumed range of uncertainties, i.e., no combination of structural weight and I_{sp} result in an unreasonable fuel mass requirement. Similar results were obtained for the HTP/CINCH concept (i.e. the weight was less than that of the current PSRE). As should be expected from the deterministic results shown in Table III, the other concepts showed significant probability of weights greater than that of the PSRE.

CANDIDATE CONCEPT EVALUATION

From a weight standpoint, the HTP/NHMF, HTP/CINCH, and NTO/MMH gel concepts were all predicted to be comparable or superior to the baseline PSRE. The CINCH and NHMF were especially promising because of the relatively high propellant specific impulse values and the lower-weight spherical propellant tanks. As weight is often directly related to cost, these systems may also have lower acquisition costs.

Weight and cost are not the only discriminating factors, however; technical risk is also a key consideration. All of the concepts presented have some degree of developmental risk. The HTP concepts would need technology development and validation of the oxidizer cooling system and the fuel catalysts, and the gel concept would need to demonstrate a feasible propellant distribution and valving system. The most risky concepts, however, are the hybrid and solid propellant concepts. The hybrid has two very difficult technology challenges: proving that ignition delay can be reduced to acceptable levels and demonstrating an adequate HTP monopropellant thruster. The solid propellant concept must be shown capable of producing the precise positioning control with a multi-tiered attitude control propulsion system and must also use aggressive materials technologies to keep the weight of the system reasonable.

Based on these considerations, the HTP/NHMF and HTP/CINCH concepts appear to offer the most promise for the PBPS application. This study has indicated that the systems can be produced at a weight (and possibly cost) lower than that of the current MM III PSRE, even considering uncertainty in the sizing presumptions. The weight may be further reduced if other structural technologies such as an isogrid shell and composite interior structure are implemented. In addition to their weight advantage, the systems also appear to be feasible in terms of technical risk, especially as contrasted to the solid and hybrid propellant concepts presented.

CONCLUSIONS

From this study, it is apparent that several "green" propellants are adequate for the PBPS application. The most promising green propellant formulations appear to be HTP/CINCH and HTP/NHMF. The propellants' performance, which approaches that of the NTO/MMH, results in sized PBPS concepts that have equivalent performance and weigh less than current Minuteman III PSRE. These propellant formulations also have a reasonable level of technical risk, mostly residing in the development of soluble fuel catalysts that are required for hypergolic ignition with HTP and in the demonstration of a low-weight oxidizer cooling system. Based on these results, it is clear that in addition to their inherent advantages in storage, personnel safety, and handling, green propellants offer the necessary performance required for land-based strategic ICBM post-boost propulsion systems.

REFERENCES

[1] "Dimethyl-2-azidoethylamine, Available Data and Recommended Additional Data", Johnson Space Center White Sands Test Facility, 28 April 2000.

[2] Funk, J.E. and Rusek, J., "Assessment of United States Navy Block 0 NHMF/RGHP Propellants", 2nd International Hydrogen Peroxide Propulsion Conference, 7-10 November 1999.

[3] Meade, C.J., Lormand, B., and Purcell, N., " Status of Non-Toxic Hypergolic Miscible Fuel Development at NAWCWD China Lake", 2nd International Hydrogen Peroxide Propulsion Conference, 7-10 November 1999.

[4] "1st Hydrogen Peroxide Propulsion Workshop", http://www.ee.surrey.ac.uk/SSC/H2O2CONF/index.htm, Surrey Space Centre website, 20 April 2000.

[5] "Niosh Pocket Guide To Chemical Hazards", http://www.cdc.gov/niosh/npg/pgintrod.html, Center for Disease Control Website, 28 May 2000.

[6] Anderson, W., "Low Cost Propulsion Using a High-Density, Storable, and Clean Propellant Combination", NASA Marshall Space Flight Center.

[7] Palaszewski, B., "Gelled Liquid Hydrogen: A White Paper", NASA Lewis Research Center.

[8] Whitehead, J.C., "Hydrogen Peroxide Propulsion for Smaller Satellites", Lawrence Livermore National Laboratory.

[9] Sarner, S.F., Propellant Chemistry, Reinhold, New York, 1966.

[10] Siegel, B. and Schieler, L., Energetics of Propellant Chemistry, J. Wiley and Sons, New York, 1964.

[11] Sutton, Rocket Propulsion Elements, An Introduction to the Engineering of Rockets, J. Wiley and Sons, New York, Sixth Edition, 1992.

[12] Keith, E., "The Peroxide Counter Revolution: Replacing Toxic Propellants in Space", International Space Propulsion Incorporated.

[13] Palaszewski, B. "Propellant Technologies: A Persuasive Wave of Future Propulsion Benefits", NASA Glenn Research Center.

[14] Mavris, D.N., DeLaurentis, D.A., "An Integrated Approach to Military Aircraft Selection and Concept Evaluation," 1st AIAA Aircraft Engineering, Technology, and Operations Congress, Los Angeles, CA, September 19-21, 1995. AIAA-95-3921

[15] German, Branscome, Frits, Yiakas, et.al., "Next Generation ICBM Post Boost Propulsion System", Proposal to the 2000 AIAA MSTC Graduate Missile Design Competition, 5 June 2000.

[16] Haag, G.S., Paul, M., Brown, R., Gibbon, D., Richardson, G., "An Experimental Investigation of 'Rocket Grade' Hydrogen Peroxide," 2nd International Hydrogen Peroxide Propulsion Conference, 7-10 November 1999.

[17] "The Decomposition of H_2O_2", http://www.uiowa.edu/~c004016b/exp10/lec10/sld007.htm, University of Iowa Website, 27 May 2000.

[18] "Trident II D-5 Fleet Ballistic Missile", http://www.fas.org/nuke/guide/usa/slbm/d-5.htm, Federation of American Scientists Website, 28 May 2000.

[19] "Minuteman Propulsion System Handbook", ICBM SE/TA Program, Strategic Systems Division, TRW, inc., September 1997.

[20] Photographs of PSRE on Display at SAC Museum, Ashland, NE, from Brian York, curator, January 2000.